Changes in working memory facilitate the transition from reactive to proactive cognitive control
during childhood

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Significance Statement

Cognitive control develops rapidly over the first decade of life, with a dominant change being a transition from reliance on “as-needed” control (reactive control) to more planful control (proactive control). This study is the first to show that working memory, above and beyond other executive functions, is critical for the enactment of proactive control during childhood. Moreover, we show that greater increases in neural activity underlying working memory link working memory ability and proactive control strategy use. Together, these data suggest that neurocognitive developments in working memory are a precondition for adopting a more mature, and adaptive, proactive control strategy. Findings are of importance because perturbations in cognitive control have been linked to mental health problems.

Abstract

Cognitive control develops rapidly over the first decade of life, with one of the dominant changes being a transition from reliance on “as-needed” control (reactive control) to a more planful, sustained form of control (proactive control). While the emergence of proactive control is important for adaptive, mature behavior, we know little about how this transition takes place, the neural correlates of this transition, and whether development of executive functions are a precondition for developing the ability to adopt a proactive control strategy. The present study addresses these questions, focusing on the transition from reactive to proactive control in a cross-sectional sample of 79 children – forty-one 5-year-olds and thirty-eight 9-year-olds. Children completed an adapted version of the AX-Continuous Performance Task while electroencephalography was recorded and a standardized executive function battery was administered. Results revealed 5-year-olds predominantly employed reactive strategies, while 9-year-olds used proactive strategies. Critically, use of proactive control was predicted by working memory ability, above and beyond other executive functions. Moreover, when enacting proactive control, greater increases in neural activity underlying working memory updating were observed; links between working memory ability and proactive control strategy use were mediated by such neural activity. Collectively, the results provide convergent evidence that the developmental transition from reactive to proactive control is dependent on neurocognitive development of specific executive functioning skills. Developments in working memory appear to be a precondition for adopting the more mature, and adaptive, proactive control strategy.

Keywords: Cognitive Control, Executive Function, Working Memory, Event-related Potential P3b, Cognitive Development

Introduction

Childhood is characterized by a period of protracted cognitive and neural development (1). Understanding how children develop the ability to prioritize cognitive demands in order to complete a goal during this period – a concept known as *cognitive control* – has become of increasing interest since perturbations in cognitive control have been linked to a variety of mental health problems in adolescence (2) and adulthood (3). However, much of the research detailing developmental changes associated with cognitive control during childhood has focused on individual cognitive skills, such as *individual* executive functions (i.e., inhibition, attentional control, and working memory) and less on the dynamic interactions *between* cognitive domains. Towards this end, an expanding body of research in the area of cognitive control aims to understand how children prepare and employ a variety of cognitive resources in order to achieve a goal (4).

The Dual Mechanisms of Control theory (DMC)(5) postulates two kinds of cognitive control with temporally distinct profiles: proactive control and reactive control. Proactive control is enacted before a control-anticipated event and requires that goal-relevant information is actively maintained in order to bias attentional and action systems. In contrast, reactive control is recruited on an as-needed basis, typically in response to the detection of conflict. While the DMC has been widely applied to explain adult cognitive control (6, 7), only a few studies have examined the development of proactive and reactive control during childhood (4, 8–10).

Emerging work suggests that children transition from heavy reliance on reactive control to a more proactive strategy during the first decade of life (11). Empirical evidence suggests this transition begins in early to middle childhood (between the ages of 6-8)(4, 8–10, 12). However, it remains unclear what neurocognitive factors support this transition from reactive to proactive control during childhood. One possibility is that young children rely on reactive control simply because they are unable to remember and maintain task-relevant information as a result of the protracted development of working memory capacity during this period (11). Indeed, work in adults implicates the same brain circuitry in both working memory and proactive control paradigms (7, 13–16). Therefore, sufficient development of working memory capacity may serve as a precondition for the developmental transition from reactive to proactive control. Indeed, some developmental evidence suggests that working memory skills support the emergence of more complex cognitive strategies (12, 17). However, other executive function skills, such as inhibitory (16, 18) or attentional control (19) may also be central to cognitive control. As such, it is unclear whether the development of working memory, over and above other executive functions, underlies the transition from reactive to proactive control.

If the development of more basic executive function skills underlies the transition from proactive to reactive control, then associated neural development during this period (1) should also coincide with this transition. That is, rapid maturation of the neural systems supporting cognitive control (20–23) might allow for more complex reasoning to come “online” during childhood and adolescence (11, 24). Specifically, if the development of working memory supports the transition from reactive to proactive control, then such a transition should be observable in a known correlate of working memory: the P3b event-related potential (ERP)(25, 26). The P3b has been shown to index the updating of working memory in adults (25) and is

also detectable during childhood (27). Critically, the P3b provides a sensitive marker of working memory that has high temporal precision, which is critical for indexing the rapid cascade of processing involved in cognitive control. If the development of working memory is a precondition for the reactive to proactive control transition, one would expect such a transition to also coincide with increased activation of the P3b.

To determine whether working memory development supports a transition to proactive control in children, we had 5-year-olds and 9-year-olds complete a series of computer-based tasks. Children performed a modified version of a cognitive control task which allows for the discrimination of proactive and reactive control (the AX-Continuous Performance Task [AX-CPT]) while electroencephalography (EEG) was collected. Additionally, participants completed a standardized cognitive battery that measured multiple domains of executive functioning including attention shifting, working memory, and inhibitory control. Consistent with prior work, we expected to observe a transition from preferential reliance on reactive control to proactive control across ages 5-9. In line with our hypothesis that working memory development supports this transition, we expected that measurement of working memory ability, over and above other executive functions, would predict this transition. Providing converging evidence for this hypothesis, we also expected that P3b activation during the AX-CPT would also predict the transition from reactive to proactive control. Moreover, we hypothesized that neurocognitive processes supporting working memory (the P3b) would *mediate* the relations between working memory skill and cognitive control strategy use.

Results

Intercorrelations between variables of interest

Table 1 presents the correlations between age, performance on the AX-CPT, and executive functioning as well as means and standard deviations.

Development and behavioral indices of cognitive control strategy use

The t-tests for the d' context measure of proactive control (context sensitivity) revealed 9-year-olds ($M = 3.08$, $SD = .72$) exhibited a greater reliance on proactive control than 5-year-olds ($M = 1.99$, $SD = .87$), $t(75) = -6.00$, $p < .001$, $d = 1.365$. Specifically, this pattern suggests 9-year-olds used the cue identity to inform their responding more than 5-year-olds, thus using more proactive strategies.

Relations between executive functions and cognitive control strategy use

A linear regression was conducted to investigate how executive functions and age group relate to cognitive control strategy. The regression was conducted by regressing age group, age-adjusted scores from all three of the NIH toolbox executive tasks (DCCS, Flanker, and List Sorting Working Memory), and interaction terms between age group and executive functioning onto the d' context score.

The model for examining how executive functioning and age group predicted the d' context ($F(7, 64) = 6.409$, $p < .001$, $R^2 = .412$) reached significance. Examination of individual predictors revealed age group significantly predicted d' context scores ($t(69) = 5.509$, $p < .001$),

which was qualified by an age group by working memory interaction ($t(69) = 2.049, p = .045$). Follow-up analyses revealed that for the 9-year-old group, working memory skill, above and beyond other executive functions, was positively predictive of the implementation of a more proactive strategy. This pattern was not evident in 5-year-olds.

Development in cognitive control strategy and neural activation

To examine differences in the P3b amplitude a 2 Group (5-year-old, 9-year-old) by 2 Condition (A cue, B cue) repeated measures ANOVA was conducted (see Figure 1 for waveforms). The model revealed a main effect for Condition $F(1, 69) = 18.306, p < .001, \eta^2 = .210$, which was qualified by a significant Group by Condition interaction $F(1, 69) = 6.171, p = .015, \eta^2 = .082$. Bonferroni-corrected follow-up tests revealed 9-year-olds had a larger P3b for B cues ($M = 7.9416, SD = 4.60614$) relative to A cues ($M = 4.9765, SD = 3.67452; F(1, 69) = 23.875, p < .001, \eta^2 = .257$), while 5-year-olds P3b did not differ by trial type (A cues: $M = 7.485, SD = 4.586$; B cues: $M = 8.271, SD = 5.377; F(1, 69) = 1.545, p = .218, \eta^2 = .022$). Additionally, on A cues, 9-year-olds had a significantly smaller P3b than 5-year-olds, $F(1, 69) = 6.158, p = .013, \eta^2 = .086$. P3b amplitude on B trials did not differ between groups, $F(1, 69) = .077, p = .782, \eta^2 = .001$.

Relations between the P3b and cognitive control strategy was examined using a Pearson's correlation. To do this, first a P3b difference score was created by subtracting the amplitude of the 'A' cue from the 'B' cue. The P3b difference score was significantly and positively correlated with the d' context score ($r(69) = .294, p = .013$) suggesting the larger the amplitude difference between the 'A' and 'B' cues, the more a proactive strategy was implemented.

Relations between executive skills, neural activation, and cognitive control strategy use

The findings described above demonstrate that both a behavioral metric of working memory ability (LSWM) and a neural index of working memory updating (P3b) both predict a greater reliance on proactive control in children. Therefore, a mediation model was conducted to investigate whether differences in P3b amplitude serve as a *neurobehavioral marker* explaining relations between working memory ability (measured via LSWM) and the implantation of a proactive strategy on the AX-CPT. To investigate this question, a single moderated mediation model was conducted (see Figure 3). The indirect effect for this model reached significance ($B = .006, SE = .003, 95\% CI = .001, .014$), suggesting that children with better working memory ability are more likely to exhibit a neural correlate of working memory updating when performing the AX-CPT and, in turn, the more likely to demonstrate use of a primarily proactive control strategy.

Discussion

The goal of the present study was to examine developmental transitions in cognitive control strategy use and identify underlying neurocognitive factors associated with that transition. Consistent with prior work (4, 11, 28) and the Dual Mechanisms of Control (DMC)(5) theory, data from the present study showed that children transition between a reliance on

reactive cognitive control strategies in early childhood (~ age 5) to proactive cognitive control strategies use in later childhood (~ age 9). Critically, data suggest that working memory, above and beyond other executive functions, is integral to the implementation of a proactive strategy in older children. Finally, a neural index of working memory updating (the P3b) was increased for children who employed a more proactive control strategy and the P3b mediated relations between behavioral assessments of working memory ability and cognitive control strategy. Together, these data are the first to show converging evidence that neurocognitive developments in working memory are a precondition for adopting a more mature, and adaptive, proactive control strategy during childhood. These findings are also of interest since perturbations in cognitive control have been linked to a variety of mental health problems (2, 3) affording an understanding of the etiology and possible factors for intervention.

In the current study, we assessed independent measures of three executive functions – inhibitory control, working memory, and attentional control - and found that age-related increases in d' context (proactive control) were specifically moderated by working memory ability. That is, while 9-year-olds as a whole exhibited increased reliance on proactive control strategies, this developmental transition was most prominent for those children also exhibiting greater working memory ability. Moreover, while children who utilized proactive strategies (i.e., 9-year-olds) also had better working memory, this pattern was not evident in younger children who did not enact such strategies, suggesting a lack of specificity amongst executive functions for reactive strategy use in young children. This pattern of findings fits nicely with a growing body of research that suggests executive functions measured in early childhood reflect a single cognitive factor and become increasingly distinct skills with age (29–31). Additionally, these data suggest a link between working memory and proactive strategy, likely driven by involvement of a dorsolateral prefrontal cortex circuitry (7, 13–16).

Our target candidate for identifying the neural correlates reflecting the transition from reactive to proactive control was the cue-locked P3b, which is thought to be reflective of cue-related updating of working memory for task-relevant information (32). We demonstrated that the more a child demonstrated increased P3b differentiation between the different types of task-relevant information given in advance of a response-event (e.g., 'A' versus 'B' cue), the more likely a child was to use a proactive strategy (i.e. the P3b magnitude predicted d' context). Specifically, 9-year-olds (vs. 5-year-olds) were more likely to display enhanced neural discrimination for different kinds of task-relevant information given in advance (i.e., larger P3b amplitude for 'B' relative to 'A' cues). This study is the first study to show links between cognitive control strategy use and differential patterns of neural activation on an AX-CPT task during early childhood. Moreover, we found that P3b amplitude reflecting working memory updating (25, 26) mediated relations between behavioral assessments of working memory ability and proactive strategy implementation, suggesting that activation of preparatory stimulus-locked classification and memory functions are critical for a proactive strategy.

The present study created a version of the AX-CPT for very young children that could be used with acquisition of EEG. Data from the present study were consistent with other studies suggesting older children (e.g., 9-year-olds) observe and use environmental cues to in order to

complete a goal, while younger children (e.g., 5-year-olds) use instantaneous stimulus-related information to drive their responding (4, 8, 10, 18). The consistency of findings was an important validation of the new task, given that slight alterations in task timings and trial proportions were necessary for the calculation of event-related potentials. However, the present study does have limitations. Of note, the sample size was modest and future studies should replicate the findings reported here in a larger—potentially longitudinal—sample.

In conclusion, evidence from the current study suggests the transition from a preferential reliance on in-the-moment (reactive) to more planful (proactive) strategies in children is contingent upon on the development of working memory. Critically, this transition relies on planning-related neural activity linked to stimulus categorization and the updating working memory. Relatedly, the P3b can be employed to index developments in working memory that predict the emergence of proactive control.

Methods

Participants

Seventy-nine children – forty-one 5-year-olds and thirty-eight 9-year-olds –were recruited for participation in this study. Following IRB approval, participants were recruited from the greater metropolitan area of a large city on the eastern coast of the United States.

Participants were excluded from participation if parents reported any current psychiatric disorders, previous brain injury, significant birth defects, significant or uncorrected visual impairments, any physical disability that would impede their ability to complete the task, and/or any prescribed medication for neurological or mental health issues. As a result, one child (age 5) was excluded. As such, our final sample consisted of forty 5-year-olds ($M_{\text{age}} = 5.35$ years; $SD = .37$ years) and thirty-eight 9-year-olds ($M_{\text{age}} = 9.05$ years; $SD = .43$ years).

Procedure

Upon arrival at the laboratory, parents were informed of all procedures, and informed consent was obtained. Children were also informed of the study procedure and written or verbal (when a child could not write his/her name) assent was obtained. Following consent, parents completed questionnaires. Children were then led to a physiology collection room where they were fitted with an EEG net and asked to perform the AX-CPT task. Following completion of the AX-CPT, the child completed the NIH toolbox assessment. Finally, all families were compensated \$20 and children selected a small prize.

Demographics Questionnaire

Parents completed one standard demographics questionnaire. Information collected included age of participant, race, current medications, and other relevant information.

Child AX-CPT Laboratory Task

An adapted child-friendly version of the AX Continuous Performance Task (AX-CPT)(5, 33–35) was administered using E-prime stimulus presentation software (Psychology Software

Tools, Inc., Sharpsburg, PA). The AX-CPT was comprised of 4 trial types – AX, AY, BX, BY (see Figure 2 for task schematic). AX trials were the target trial for this task and had a different response (either 1 or 4 on a button box) than the other three trial types. Consistent with past EEG and ERP studies using the AX-CPT, AX trials were presented 55% of the time while each other trial type (AY, BX, BY) was presented 15% of the time (36). Trials were presented in a random order.

Consistent with past studies in children (4), the traditional letter-based AX-CPT stimuli were replaced with cartoon figures and participants only responded once to the probe stimuli, as opposed to responding after both the cue and probe in the adult versions of the task. Each trial began with a centrally located fixation cross followed by one cue stimulus (A or B), which was presented for a duration of 500 ms. The cue stimulus was followed by a randomized interstimulus interval of 1400 to 1600 ms. Finally, one of two probe stimuli (X or Y) was presented until the participant responded or until the conclusion of a predetermined response window. To encourage sustained attention, participants were encouraged to respond as quickly as possible and a dynamic response window was used. Consistent with past research (4), the initial response window was set to 6000 ms, but was adjusted to be a maximum of 150% of the previous eight correct responses. Eight versions of the task were programmed to ensure cue and probe pairings were counterbalanced across participants.

Before beginning the task, participants completed a practice block of 12 trials, which had to be completed at 70% accuracy or greater in order to move forward. Stimuli were presented in blocks of 40 trials. Participants were encouraged to complete as many blocks as possible, with a maximum of eight blocks (320 stimuli pairs), although participants only completed around six blocks on average ($M_{\text{trials}} = 236.13$; $SD = 52.07$; see S1 for block-level analyses). To ensure participants understood task instructions, participants with <60% accuracy on BY trials (trials without a target cue or probe) were excluded from all analyses ($N=1$; see S2 for more information on data cleaning)(4). A behavioral composite indexing proactivity - known as d' context – was computed (information on d' and A-cue bias calculation can be found in S2; to see investigations using accuracy and reaction time, see S3; to see investigations using the Proactive Shift Index, see S4; to see investigations of A-cue bias see S5). The d' context metric reflects how sensitive a participant is to the identity of the cue (A or B) and increases with more proactive strategy use.

EEG Recording and Processing

Continuous EEG was recorded using a 128-channel Geodesic Sensor Net and sampled at 500 Hz (Electrical Geodesic, Inc., Eugene, OR). Before data collection, all electrode impedances were reduced to below 50 k Ω . During collection, electrodes were referenced to electrode Cz. Following data collection, data were re-referenced to an average reference. All EEG/ERP processing was completed using EEGLAB (37) and ERP PCA Toolkit (38).

Data were filtered offline using a digital band-pass FIR filter from .3-50 Hz. Data were segmented separately for 'A' cue and 'B' cue trials from 200 ms before the presentation of the cue to 1000 ms following cue presentation. Only trials that resulted in a correct behavioral response were analyzed. Channels were marked bad if the electrode amplitude exceeded 150 μV or if a channel differed by more than 40 μV from any neighboring channel. Channels were

marked globally bad if the correlation between neighboring channels was less than .30 or if the channel was bad on greater than 20% of trials (A trials: 4.9% of channels, B trials: 4.9% of channels). Trials were marked bad if more than 20% of channels were determined to be bad (A trials: 27.7% of trials, B trials: 27.2% of trials). Bad channels on remaining good trials were replaced using spherical spline interpolation (39). Participants needed at least ten artifact-free trials in each condition to be included in the analysis. Consistent with other developmental work, the P3b was evaluated as the mean amplitude between 350-650 ms (27) following cue presentation at a grouping of parietal electrodes at the midline surrounding electrode Pz (electrode numbers 54, 61, 62, 67, 72, 77, 78, 79,).

NIH Toolbox Childhood Cognition Battery

The NIH toolbox cognition battery (40) is a validated cognitive assessment tool constructed by a team of scientists in collaboration with the National Institutes of Health (NIH). The NIH Early childhood cognitive assessment battery includes five short tasks aimed at assessing cognitive functioning in children (41). Three tasks are specifically aimed at assessing executive functions in young children: the Dimensional Change Card Sort (DCCS) as a measure of attention shifting (42, 43), the Flanker as a measure of inhibitory control (44), and the List Sorting Working Memory test as a measure of working memory (45). As is standard for all NIH Toolbox assessments, task data was scored using the NIH Toolbox iPad app. All tasks have been normed and validated for longitudinal cognitive measurement from age 3 to 85 (46–48).

Data Analysis Plan

Before exploring the main study aims, multiple Pearson's correlations were conducted to explore the intercorrelations between age, performance on the AX-CPT, the P3b, and executive functioning.

Analyses of Control Strategy.

Consistent with past studies utilizing the AX-CPT to assess cognitive control strategy use, a signal detection theoretic measures – known as d' context was computed (35, 49). Higher scores for the d' context measure reflect a greater reliance on proactive control; group differences in d' context were tested using an independent samples t-tests.

Analysis of Associations Between Executive Functions and Control Strategy.

A linear regression was conducted to examine the relations between age, executive functions, and cognitive control strategy. The regression had age group (dichotomously coded) as well as age-corrected scores from all three of the NIH toolbox executive tasks (DCCS, Flanker, and List Sorting Working Memory) entered into the model as predictors with d' serving as the outcome. Additionally, interaction terms for age group by each executive task were entered into the model in order to examine how executive skills associated with proactive and reactive strategy use in each age group.

Testing Relations Between Neurocognition and Control Strategy.

Analyses of the relations between cognitive functioning and cognitive control strategy use took place in two steps. The significance level was set at .05 for all analyses.

First, the cue-locked P3b was assessed using a 2 Group (5-year-old, 9-year-old) by 2 Condition (A cue, B cue) repeated measures ANOVA. Significant main and interaction effects

were explored using paired sample t-tests for within-subjects effects and independent samples t-test for between-subject effects. Bonferroni corrections for multiple comparisons were applied when necessary. Relations between the P3b component and cognitive control strategy were examined by correlating component amplitude with d' context.

Second, in order to investigate whether the relation between executive functioning and cognitive control were mediated by neural activation, a mediation model was conducted for significant predictors in the previous analysis step (testing relations between executive function skills and cognitive control strategy) were conducted using the PROCESS macro for SPSS (version 3)(50). Indirect effects were tested using a percentile bootstrap estimation approach with 10,000 samples.

Participant Inclusion.

For all behavioral and ERP analyses, one 5-year-old was excluded due to less than 60% accuracy on BY trials. Additionally, for the P3b analyses, one 9-year-old was excluded due to refusing the EEG cap and a total of five 5-year-olds were excluded: three for refusing the EEG cap and two due to an insufficient number of correct and artifact-free B trials.

Participants were excluded on a task-by-task basis for analyses examining associations between cognitive control strategy use and executive functioning. For the Flanker and DCCS, one child was excluded due to toolbox refusal (see Table 2 for inclusion). For the List Sorting Working Memory (LSWM) task, a total of five 5-year-olds were excluded – one due to time constraints and four who did not complete enough items to yield a score.

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Figure 1. A) ERP waveforms for the P3b (top) for 5-year-olds. B) ERP waveforms for the P3b (bottom) for 9-year-olds.

Figure 2. Child AX-CPT Task Schematic.

Figure 3. Mediation model. Unstandardized effects reported with standard errors in parentheses.

Table 1. Zero-order correlations, means, and standard deviations of measures of interest.

	1.	2.	3.	4.	5.	6.
1. Age	1					
2. d' context	.613**	1				
3. ΔP3b	.279*	.294*	1			
4. Flanker – (inhibitory control; uncorrected score)	.769**	.516**	.296*	1		
5. DCCS – (attention shifting; uncorrected score)	.730**	.415**	.281*	.695**	1	
6. LSWM – (working memory; uncorrected score)	.792**	.553**	.436*	.737**	.615**	1
M	7.1872	2.5257	1.9219	75.3421	78.2368	83.0139
SD	1.8934	.96255	3.8250	21.3076	21.2112	18.3744

**<.01 *<.05

Table 2. Participant inclusion by age for each measure of interest.

Enrolled		Behavioral		P3b ERP		Flanker		DCCS		LSWM	
<u>5</u>	<u>9</u>	<u>5</u>	<u>9</u>	<u>5</u>	<u>9</u>	<u>5</u>	<u>9</u>	<u>5</u>	<u>9</u>	<u>5</u>	<u>9</u>
41	38	39	38	34	37	38	38	38	38	34	38

Supplementary Information for

Changes in working memory facilitate the transition from reactive to proactive cognitive control during childhood

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Supplementary Information Text

S1. Learning effects during the AX-CPT.

To ensure that participants understood the task and that substantial task learning did not take place during the earlier blocks, performance was examined block-by-block within each age group (see Figure S1). For both the 5-year-olds and 9-year-olds, performance on any single block did not significantly differ from either neighboring block (5-year-olds: $p_s > .092$; 9-year-olds: $p_s > .097$). Importantly, there also did not appear to be any learning effect between Block 1 and 2 (as evidenced by no increase in accuracy), which suggests that the practice trials were sufficient for learning task rules.

S2. Cleaning and scoring of AX-CPT Behavioral Data.

Cleaning of Behavioral Data.

Trials with response times faster than 100 ms were removed all from analyses. Additionally, reaction times (RTs) from correct trials for each trial type were z-transformed with respect to each subject's grand mean RT across all correct trials to increase statistical power and correct for individual differences in overall processing speed (1, 2). Accuracy was calculated as the number of correct trials divided by the total number of trials. Accuracy and response times were separately averaged for AX, AY, BX, and BY trials for each participant in each condition.

Computation of d' context and A-cue bias

The d' context measure (3, 4) compares the sensitivity to the 'X' probe in the presence and absence of an informative contextual cue, and thus provides a measure of sensitivity to context. To compute this measure we examined performance on two trial types -- AX and BX. These trial types have the same probe (X) but different cues (A vs B). To calculate the measure, we took hits on AX trials and subtracted the false alarms on BX trials. For instance, if the participant guessed every time they saw an 'X' probe because they did not remember the cue, they would have approximately 50% AX hits and 50% BX false alarms -- a score near 0. The more a participant remembers the cue identity (A vs B) the more accurate they should be on AX and BX trials, which increases the AX hit rate and decreases the BX false alarm rate, thus yielding a higher d' context score. The higher the score, the more cue identity informs a response. Hit rates and false alarms with a value of zero or one were corrected with methods

consistent with past research (5). A-cue bias, provides a measure of the tendency to differentially prepare for target responses based on the presentation of an A cue (6, 7). The A-cue index was calculated by computing a criterion score using hits on AX trials and false alarms on AY trials. These trial types have the same cue (A) but different cues (X vs Y). To calculate the measure, we take hits on AX trials and subtract the false alarms on AY trials. The A-cue bias measure indicates the general tendency to make a target response following an A-cue. Positive values indicate a positive bias towards 'X' responding, and are predicted to increase in proactive when proactive control is used. For both d' context and A-Cue bias computations, a correction was applied to cases in which there was a hit rate of 1 (hit rate = $2-(1/N)$; N = target trials) or a false alarm rate of 0 (false alarm = $1-2-(1/N)$; N = number of non-target trials), which has been shown to allow for an unbiased estimation of signal detection theoretic measures (5).

S3. Analyses examining Accuracy and Reaction Time on the AX-CPT.

Behavioral analyses of accuracy and reaction time took place in two steps. The significance level was set at .05 for all analyses and Bonferroni corrections for multiple comparisons were utilized where appropriate. First, accuracy and reaction times were analyzed separately using a 2 Group (5-year-old, 9-year-old) by 2 Condition (AY, BX) repeated measures ANOVA. Second, to examine whether cue or probe relationships were driving responding within each age group, partial correlations, controlling for AX reaction times, were conducted for AY, BX, and BY trials.

Mean accuracy and RTs by condition are reported in Table S1. To examine whether there were developmental differences in accuracy and reaction time (RT) on the AX-CPT task, two 2 Group (5-year-old, 9-year-old) by 2 Condition (AY, BX) repeated measures ANOVAs were conducted. The model examining accuracy revealed a main effect for Group $F(1, 75) = 11.82, p = .001, \eta^2 = .136$ and a marginal main effect of Condition $F(1, 75) = 3.13, p = .081, \eta^2 = .040$, both of which were qualified by a significant group by trial interaction $F(1, 75) = 21.62, p < .001, \eta^2 = .224$. Bonferroni-corrected follow-up tests revealed that 5-year-olds performed better on AY ($M = 84.97\%, SD = 11.09\%$) trials relative to BX trials ($M = 72.13\%, SD = 16.81\%$), $F(1, 75) = 20.87, p < .001, \eta^2 = .218$. The reverse was true for 9-year-olds who showed better performance on BX trials ($M = 88.92\%, SD = 10.81\%$) relative to AY trials ($M = 83.16.2\%, SD = 12.22\%$), $F(1, 75) = 4.09, p = .047, \eta^2 = .052$. Finally, 5-year-olds ($M = 72.13\%, SD = 16.81\%$) performed significantly worse than 9-year-olds ($M = 88.92\%, SD = 10.81\%$) on BX trials $F(1, 75) = 27.031, p < .001, \eta^2 = .265$. The two groups did not differ in performance on AY trials $F(1, 75) = .467, p = .497, \eta^2 = .006$.

Analyses examining group differences in reaction time revealed a main effect for Condition $F(1, 75) = 90.640, p < .001, \eta^2 = .547$ but no main effect of Group, which was not unexpected due to the z-transformation procedure $F(1, 75) = 2.07, p = .155, \eta^2 = .027$. A significant Group by Condition interaction also emerged $F(1, 75) = 8.55, p = .005, \eta^2 = .102$. Bonferroni-corrected follow-up tests revealed that both 5-year-olds and 9-year-olds were slower on AY trials (5: $M = .24, SD = .29$; 9: $M = .34, SD = .27$) relative to BX (5: $M = -.11, SD = .32$; 9: $M = -.32, SD = .24$) trials (5: $F(1, 75) = 22.04, p < .001, \eta^2 = .227$; 9: $F(1, 75) = 76.45, p < .001, \eta^2 = .547$).

.001, $\eta^2 = .505$. Additionally, 5-year-olds ($M = -.11$, $SD = .32$) were significantly slower than 9-year-olds ($M = -.32$, $SD = .24$) on BX trials $F(1, 75) = 10.041$, $p = .002$, $\eta^2 = .122$. The two groups did not differ in the z-transformed reaction time on AY trials $F(1, 75) = 2.589$, $p = .112$, $\eta^2 = .033$.

To examine whether cue or probe relation drove responding within each age group, partial correlations, controlling for AX reaction times, were conducted for AY, BX, and BY trials (see Figure S2). Consistent with the notion that reactive control is associated with probe identity, 5-year-olds showed a significant correlation between reaction times on the two trial types that share a probe -- AY and BY trials ($r(36) = .410$, $p = .010$). 5-year-old reaction times between AY and BX ($r(36) = -.118$, $p = .481$) and BY and BX ($r(36) = .007$, $p = .964$) were not significantly associated. Consistent with the notion that proactive control is associated with cue identity, 9-year-olds showed a significant correlation between reaction times on the two trial types that share a cue -- BX and BY trials ($r(35) = .631$, $p < .001$). 9-year-old reaction times between AY and BX ($r(35) = .123$, $p = .468$) and AY and BY ($r(35) = .161$, $p = .340$) were not significantly associated.

S4. Investigation of the Proactive Shift Index.

Computation of the PSI Sum measure.

The Proactive Shift Index (PSI) (8), compares performance on AY trials relative to BX trials. Higher scores indicate increased use of proactive control and lower scores indicate more reactive strategy use. The PSI was computed for both errors and RT and then a sum was computed by adding the PSI for errors to the PSI for RT. The equation used to compute the PSIs was as follows:

$$PSI = \frac{(AY - BX)}{(AY + BX)}$$

Consistent with past research (8), the following correction was made for the PSI accuracy computation to avoid errors equaling to zero: $(\text{error} + 0.5) / (\text{frequency of trials} + 1)$.

Consistent with past studies utilizing the AX-CPT to assess cognitive control strategy use, three PSI indices were computed (8) – one for PSI accuracy, one for PSI RT, and the combined PSI sum (see Table S2 for correlations with measures of interest). Group differences in the PSI indices were tested using an independent sample t-test for the sum composite.

Group Differences in the PSI Sum measure.

Group differences in the PSI sum measure, the test revealed that 9-year-olds ($M = .37$, $SD = .51$) used a proactive strategy, while 5-year-olds ($M = -.14$, $SD = .45$) used a reactive strategy, $t(75) = -4.68$, $p < .001$, $d = 1.060$.

Relations between PSI Sum and neural activity

Relations between the P3b and cognitive control strategy use were examined using Pearson's correlations. First, a P3b difference score was created by subtracting the amplitude of

the 'A' cue from the 'B' cue. The P3b difference score was significantly and positively correlated with the PSI sum score ($r(69) = .346, p = .003$).

S4. Investigation of the A-cue Bias.

Group Differences in A-cue Bias.

A-cue bias reflects the strategy used to differentially prepare for the probe stimulus (X/Y) responses based on the presentation of a single cue (e.g., A). A-cue bias increases with more proactive strategy use sum (see Table S3 for correlations with measures of interest) (7).

Group differences in A-cue bias was tested using an independent samples t-tests. The t-test for the A-cue bias revealed that 9-year-olds ($M = .32, SD = .29$) had a larger a-cue bias than the 5-year-olds ($M = .10, SD = .30$), $t(75) = -3.334, p = .001, d = .745$.

Relations between A-cue bias and executive functioning

A linear regression was conducted to examine the relations between age, executive functions, and a-cue bias. The regression had age group (dichotomously coded) as well as age-corrected scores from all three of the NIH toolbox executive tasks (DCCS, Flanker, and List Sorting Working Memory) entered into the model as predictors. Additionally, interaction terms for age group by each executive task were entered into the model in order to examine how executive skills associated with proactive and reactive strategy use in each age group.

The model examining A-cue bias also reached significance ($F(7, 64) = 3.136, p = .007, R^2 = .255$). The only individual predictor that reached significance was age group. However, there was a marginally significant age group by inhibitory control interaction ($t(69) = 1.863, p = .067$). Follow-up analyses were not conducted, but the marginal nature of this effect may highlight a path for future research.

Relations between A-cue bias and neural activity

Relations between the P3b component and A-cue bias were examined using a Pearson's correlation. The P3b difference score was significantly and positively correlated with the A-cue bias ($r(69) = .436, p < .001$) suggesting that the larger the amplitude difference between the 'A' and 'B' cues, the more a child was likely to bias their responding based on the presentation for a 'A' cue.

Fig. S1. Performance by block and age group. Error bars reflect the standard error of the mean.

Fig. S2. Partial correlations between AY, BX, and BY reaction times while controlling for reaction times on AX trials. Pearson's correlations are reported in circle overlaps and significant correlations are marked with an asterisk.

Table S1. Descriptive statistics for each age group (mean and standard deviation in parentheses) and group differences (t value and significance in parentheses).

	<u>5 Year</u> (N=39)	<u>9 Year</u> (N=38)	<u>5 vs 9</u>
Total Trials Completed	217.79 (50.00)	260.05 (33.37)	-4.458 (<.001)
AX Accuracy	88.67 (8.1)	94.08 (6.1)	-3.411 (.001)
AY Accuracy	84.97 (11.1)	83.16 (12.2)	.441 (.660)
BX Accuracy	72.13 (16.8)	88.92 (10.8)	-5.301 (<.001)
BY Accuracy	91.62 (7.1)	97.76 (3.7)	-3.221 (.002)
AX RT (not z-transformed)	1502.53 (426.13)	748.18 (347.23)	8.603 (<.001)
AY RT (not z-transformed)	1730.23 (423.95)	825.17 (329.54)	10.507 (<.001)
BX RT (not z-transformed)	1430.19 (635.46)	591.75 (312.62)	6.998 (<.001)
BY RT (not z-transformed)	1466.67 (405.45)	595.06 (302.30)	10.713 (<.001)

Table S2. Correlations between PSI and other variables of interest.

	2. PSI Accuracy	3. PSI RT	4. PSI Sum
1. Age	.500**	.252*	.503**
2. PSI Accuracy	1	.374**	.973**
3. PSI RT	.374**	1	.579**
4. PSI Sum	.973**	.579**	1
5. d' context	.639**	.182	.607**
6.A-cue bias	.703**	.478**	.738**
7. Flanker	.437**	.356**	.473**
(uncorrected)			
8. DCCS	.413**	.320**	.443**
(uncorrected)			
9. LSWM	.401**	.202	.410**
(uncorrected)			
M	-.0375	.1490	.1115
SD	.48013	.13692	.54627

**<.01 *<.05

Table S3. Zero-order correlations, mean, and standard deviation for A-cue bias.

	3. A-cue bias
1. Age	.382**
2. d' context	.528**
3.A-cue bias	1
4.ΔP3	.463**
7. Flanker (uncorrected)	.414**
8. DCCS (uncorrected)	.336**
9. LSWM (uncorrected)	.347**
M	0.2084
SD	0.3148

**<.01 *<.05

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